



Functional Requirement Specification

PIP-II FRS

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	9/2/10	All	Draft version 4.5 posted to Project X DOCDB
	9/23/10	All	Draft version 4.6 posted to Project X DOCDB
	11/10/10	All	Draft version 4.8 posted to Project X DOCDB, PX retreat conclusions included
	1/5/11	4	Draft version 4.9 change FE to 162.5 MHz, 5 mA, 10 % DF upgrade
	10/5/11	4.11	Draft version 4.11 change first CM to 162.5 MHz
	10/14/11	4.12	Update for high intensity workshop
	11/8/12	All	Update to reflect staging, including joint 1/3 GeV operations at 1/3 MW
	7/29/14	All	Updated to reflect migration to Teamcenter.
	3/17/17	All	Updated to reflect PIP-II project scope; version approved by Director's Office (CRO and CAO).

TABLE OF CONTENTS

- 1. Introduction**
- 2. Mission Need**
- 3. Design Criteria**
- 4. Key Assumptions, Interfaces, and Constraints**
- 5. Facility Scope**
- 6. Functional Requirements**
- 7. Safety Requirements**
- 8. References**

1. Introduction

Proton Improvement Plan-II (PIP-II) encompasses a set of upgrades and improvements to the Fermilab accelerator complex aimed at supporting a world-leading neutrino program over the next several decades. PIP-II is an integral part of the strategic plan for U.S. High Energy Physics as described in the Particle Physics Project Prioritization Panel (P5) report of May 2014 [1], and formally established via the Mission Need Statement (MNS) and CD-0 in November 2015 [2]. As an immediate goal PIP-II is focused on upgrades to the Fermilab accelerator complex capable of providing proton beam power in excess of 1 MW on target at the initiation of the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) program, currently anticipated for the mid-2020s. PIP-II is a part of a longer-term vision of establishing a high-intensity proton facility that is unique within the world, ultimately leading to multi-MW proton beam capabilities at Fermilab.

The P5 report contains two recommendations specifically aimed at meeting these goals:

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

The P5 report quantifies the requirements associated with these recommendations: “..we set as a goal a mean sensitivity to CP violation of better than 3σ ...over 75% of the range of possible values of the unknown CP-violating phase δ_{CP} . Using a wideband neutrino beam produced by a proton beam...requires...600 kt*MW*yr of exposure assuming systematic uncertainties of 1% and 5% for the signal and background respectively. The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power.” Additionally, the P5 report addresses the requirements for muon-based physics: “Looking farther into the future, progress in precision physics and rare processes will be shaped partly by what particle physicists learn in the coming decade. Upgrades to the accelerator complex at Fermilab (PIP-II and additional improvements) will offer opportunities to further this program. For example, combined with modest upgrades to Mu2e, improvements in the Fermilab accelerator complex potentially could provide increased sensitivity (by a factor of ten) to muon-to-electron conversion and allow one to search for this very rare process in different nuclei. This will provide crucial clues on the nature of the new physics revealed in the event of an observation in the next-generation experiments.”

These requirements set the goals for an upgrade to the Fermilab accelerator complex to support long-term research in neutrinos and muons, both in terms of initial capabilities and future upgradability.

Following acceptance of the P5 report by the Department of Energy/Office of High Energy Physics, an international collaboration was formed to mount the Deep Underground Neutrino Experiment (DUNE) based on the LBNF at Fermilab. Shortly thereafter the Office of Science approved a Mission Need Statement for PIP-II followed by Critical Decision-0 (CD-0).

2. Mission Need

The Mission Need Statement for PIP-II represents the implementation of the P5 plan by the Department of Energy. The MNS identifies two primary goals:

1. To reduce the time required for LBNF/DUNE to achieve world-first results.
2. To sustain high reliability operation of the Fermilab complex.

The MNS establishes 1.2 MW as the goal for beam power delivered from the Main Injector following implementation of PIP-II. The MNS also describes the need to implement PIP-II in a manner that will allow a subsequent doubling of power delivered from the Main Injector based on future upgrades, and the desirability of maintaining compatibility with a subsequent upgrade to continuous wave (CW) operations in support of a broader spectrum of particle physics research opportunities, including muons.

3. Design Criteria

Design criteria for PIP-II are established on the basis of the P5 report and the approved MNS as follows:

- Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations;
- Support the current 8-GeV program at Fermilab including the Mu2e, g-2, and short-baseline neutrinos experiments;
- Provide a platform for extension of beam power to LBNF to >2 MW;
- Provide a path to increase the beam power to the Mu2e experiment to ~ 100 kW, with a duty factor of up to 100%; Provide a platform for extension of capability to high duty factor/higher beam power operations to multiple experiments simultaneously.

The above capabilities should be provided in a cost-effective manner.

4. Key Assumptions, Interfaces and Constraints

Assumptions related to the development of PIP-II are contained in the Assumptions Document prepared in advance of CD-1 [3].

5. Facility Scope

The PIP-II concept is based on an 800-MeV superconducting linac (SC Linac), injecting into the existing 8-GeV Booster via a newly constructed injection area, augmented by upgrades to the Main Injector and Recycler ring to allow them to accommodate the high Booster intensities enabled by the

SC Linac. This concept was identified by DOE/OHEP as the preferred option following review of the Analysis of Alternatives report prepared after CD-0 [4].

Specific scope elements of the PIP-II project are expected to include:

- An 800-MeV superconducting H⁻ linac, constructed of CW-capable components, and operating initially in pulsed beam mode. Note: Full CW RF operational capability is expected to be available initially.
- Beam transport of 800-MeV H⁻ from the SC Linac to the Booster, including accommodation of a beam dump capable of accommodating full intensity at low (~1%) duty factor and future delivery of beam to the Muon Campus.
- A new injection area in the Booster to accommodate 800-MeV injection.
- Modifications to the Booster to accommodate a 50% increase in beam intensity
- Modifications to the Main Injector and Recycler Ring to support acceleration and extraction of high intensity/high power proton beams over the range 60-120 GeV.
- Associated conventional facilities including enclosures, equipment galleries, and utilities. The linac enclosure will be constructed with a length to accommodate four HB650 cryomodules beyond the nominal complement required for 800 MeV.

6. Functional Requirements

The following function requirements meet the design criteria listed above in a cost effective manner, while providing flexibility for future development of the Fermilab accelerator complex.

Superconducting Linac

Requirement	Description	Value
L1	Delivered Beam Energy (kinetic)	800 MeV
L2	Beam Particles	H ⁻
L3	Beam Pulse Length	0.54 msec
L4	Particles per Pulse	6.7×10^{12}
L5	Pulse Rate	20 Hz
L6	Average Beam Current during Pulse	2 mA
L7	Maximum Beam Current during Pulse	5 mA
L8	Maximum Bunch Intensity	1.9×10^8
L9	Minimum Bunch Spacing	6.2 nsec (1/162.5 MHz)
L10	Bunch Pattern	Programmable and arbitrary

Requirement	Description	Value
L11	RF Frequency	162.5 MHz and harmonics thereof
L12	Bunch Length (rms)	<4 psec
L13	Transverse Emittance (rms, normalized)	0.3 mm-mrad
L14	Longitudinal Emittance (rms)	<1.1 keV-nsec

8-GeV Booster

Requirement	Description	Value
B1	Injection Energy (kinetic)	800 MeV
B2	Extraction Energy (kinetic)	8 GeV
B3	Beam Particles	Protons
B4	Particles per Pulse	6.5×10^{12}
B5	Pulse Rate	20 Hz
B6	Capture/Acceleration Efficiency	97%
B7	Maximum Bunch Intensity	8.1×10^{10}
B8	RF Frequency	44.7-52.8 MHz
B9	Bunch Length (97%)	8 nsec
B10	Transverse Emittance (rms, normalized)	2.7 mm-mrad
B11	Longitudinal Emittance (97%)	0.08 eV-sec

Recycler Ring/Main Injector

Requirement	Description	Value
M1	Injection Energy (kinetic)	8 GeV
M2	Delivered Beam Energy	60-120 GeV
M3	Beam Power (60-120 GeV)	1.0-1.2 MW
M4	Beam Particles	Protons
M5	Particles per Pulse	7.5×10^{13}

Requirement	Description	Value
M6	Cycle Time (60-120 GeV)	0.7-1.2 sec
M7	Slip-stacking/Acceleration Efficiency	97%
M8	Extracted Beam Pulse Length	~10 μ sec
M9	Bunches per Pulse	~500
M10	Bunch Spacing	18.8 nsec (1/53.1 MHz)
M11	Transverse Emittance (rms, normalized)	3.3 mm-mrad

Integration and Upgradability

Requirement	Description	Value
I1	The siting of the PIP-II facility will be consistent with future replacement of the existing 8-GeV Booster with either an 8 GeV Rapid Cycling Synchrotron or superconducting pulsed linac	
I2	The siting of the PIP-II facility will be consistent with future upgrades to provide 100 kW beams to the Mu2e hall on the Muon Campus	
I3	The SC Linac will be constructed of components capable of operating in CW mode, following modest upgrades	
I4	The SC Linac will be constructed in a manner that allows installation and commissioning without interruption to ongoing accelerator operations	
I5	Residual Activation from Uncontrolled Beam Loss in areas requiring hands-on maintenance.	<20 mrem/hour (average) <100 mrem/hour (peak) @ 1 ft
I6	Scheduled Maintenance Weeks/Year	8
I7	SC Linac Operational Reliability	90%
I8	60-120 GeV Operational Reliability	85%
I9	Facility Lifetime	\geq 40 years

7. Safety Requirements

The Project will be built to applicable DOE and FNAL engineering, safety, and radiation standards as outlined in the Fermilab Engineering Manual [5] and Fermilab ES&H Manual [6].

8. References

[1] “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context”, Report of the Particle Physics Project Prioritization Panel, May 2014

http://science.energy.gov/~media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf

[2] PIP-II Mission Need Statement

[3] PIP-II Project Assumptions Document, PIP-II Document #144

<http://pip2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=144>

[4] Analysis of Alternatives: Proton Improvement Plan-II, PIP-II Document #107

<http://pip2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=107>

[5] Fermilab Engineering Manual

http://www.fnal.gov/directorate/documents/FNAL_Engineering_Manual_REVISED_070810.pdf

[6] Fermilab ES&H Manual

<http://esh.fnal.gov/xms/ESHQ-Manuals/FESHM>